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ABSTRACT

This paper describes a model for the adolescent's understanding of the motion of objects, and the application of this model to the design of beginning physics instruction in mechanics. Students' difficulties in learning classical Newtonian mechanics are described and integrated into current cognitive science research. Research findings on physics schemata and physics problem solving strategies are reviewed, and previous research by the authors is described which led to the development of the model for the cognitive structure for uninstructed adolescents' understanding of the motion of objects. (CS)

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A MODEL OF ADOLESCENTS' UNDERSTANDING OF PHYSICAL PHENOMENA AND ITS APPLICATION TO INSTRUCTION

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> Most science textbooks can be criticized by drawing attention to the fact...that these books are chiefly concerned with the statements of results. Usually the most general results are put near the beginning of the textbook. A textbook in physics begins by telling about molecules and the constitution of matter or by giving some of the most compactly formulated statements about the principles of mechanics...The degree of enthusiasm of the ordinary student for these introductions which he gets in the textbooks is very slight indeed...The student, confronted by these verbal additions to his experience, gets into the habit of thinking of science as verbal additions to experience, and he faithfully learns the words and keeps them in store against the time when the teacher demands them. (Judd, 1915, pp. 334-336)

Introduction

One trend in cognitive psychology during the past decade has increasingly focused the attention of both theoretical and empirical researchers on learning tasks representative of those which students encounter in school instruction (Greeno, 1980). This should be a welcomed development for many educators, who are continually concerned

about children's success in learning in schools. Science educators who seek to improve instruction, so as to help overcome the difficulties many obviously face in learning science concepts, should particularly welcome the recent research developments in cognitive psychology because it holds the promise of a new theoretical basis for their work. A theoretically organized and systematically verified foundation is an essential requisite for substantial improvement of science instruction and for the amelioration of conceptual difficulties students experience in learning science. However, no satisfactory theoretical model of adolescents' understanding of physical phenomena currently exists to base science instruction upon. This paper describes such a model for adolescents' understanding of the motion of objects, and the application of the model to the design of beginning physics instruction in mechanics.

We begin by describing the relevance of the instructional problem that interests us, namely, students' difficulties in learning classical Newtonian mechanics. Then, turning to cognitive science research which has bearing on the problem, we integrate relevant research strands. We review both research findings on physics schemata and physics problem solution strategies of experts and novices. Following a brief review of the research on semantic memory structure that demonstrates the impact of existing knowledge in memory on the processing and comprehension of text, we describe our own previous research leading to the development of a model of the cognitive structure for uninstructed adolescents' understanding of the motion of objects. The review of research relevant to the

instructional problem concludes with a discussion of what is both known and conjectured concerning the modification of students' cognitive states.

Our model of adolescents' understanding of the motion of objects is expressed in terms of schemata and their characteristics. The model of experts' physics knowledge developed by Chi, Feltovich, and Glaser (in press) is also expressed in the same terms. This commonality facilitates the models' application, which this paper will take up next. We here address the question of how changes in students' motion-of-objects schemata may be effected through instruction.

By comparing experts' and uninstructed students' schemata, we derive a description of the goal state for physics problem-solving instruction, as well as detailed specifications of the changes required in the students' schemata to achieve the desired goals. Also derived from the comparison of schemata is the suggestion of an instructional mechanism to bring about an essential schema change, namely, the qualitative analysis of physics problems. Considering the cognitive science research on problem solving strategies, text comprehension, and schema change, we arrive at the outlines of an instructional strategy designed to be used with beginning physics students studying mechanics in order to develop their skills in analyzing qualitative problems. The instructional strategy we propose is engaging the students in dialogues as they seek to solve problems.

We hypothesize that the proposed instructional strategy will be effective in producing changes in the motion-of-objects schemata of

beginning physics students. We further hypothesize that, after completion of the specified instruction, the students' schemata will have several significant features which are characteristic of the mechanics schema of a physics expert. The closing section of this paper contains the description of a research plan to test these hypotheses. This research will provide, not only a test of the proposed instructional strategy and prototype instructional materials, but also a further verification of the psychological principles which are embodied in the instructional strategy and materials.

The instructional problem

There is general agreement among physics instructors and students that mechanics is difficult to teach and to learn (Kolody, 1977). Students have difficulty comprehending classical mechanics, and physics instructors often express disappointment with the outcome of their efforts to instruct students in classical mechanics. This instructional problem has been discussed at length in the literature of physics education where various underlying causal factors contributing to the problem have been suggested (Hudson and McIntire, 1977; Gerson and Primrose, 1977; Halley & Eaton, 1975). One of these factors, in the view of some physicists, philosophers of physics, and, more recently, investigators of the learning of physics, is that students come to introductory physics courses with firmly embedded conceptualizations of how and why objects move. These conceptualizations have some characteristics in common with an Aristotelian view of the world. Dijksterhuis (1969) notes that

historically a great effort was necessary to outgrow the Aristotelean view of motion and that:

> To this day every student of elementary physics has to struggle with the same errors and misconceptions which then had to be overcome, and on a reduced scale, in the teaching of this branch of knowledge in schools, history repeats itself every year. The reason is obvious: Aristotle merely formulated the most commonplace experiences in the matter of motion as universal scientific propositions, whereas classical mechanics, with its principle of inertia and its proportionality of force and acceleration, makes assertions which not only are never confirmed by everyday experience, but whose direct experimental verification is fundamentally impossible ... (p. 30)

These and other writings by physicists, physics educators and philosophers of science suggest that in the learning of classical mechanics a situation exists wherein the student's pre-instructional conceptualization of the subject-matter domain is in clear conflict with the canonical view of that subject-matter domain which the student will be required to learn.

Educators cite various reasons for the apparent opacity of physics, especially mechanics, and have attempted various resolutions of the difficulty. These efforts are important because they offer potential leads to a better understanding of the process of science learning. Variables that may contribute to students' success in learning physics that have been investigated, at least tentatively, include: (1) mathematical skills, (2) general level of cognitive development, and (3) specific cognitive processes (e.g., Arons, 1976; Renner, Grant, & Sutherland, 1978). The basic strategy used by

science educators to investigate these variables is to identify a single student characteristic (level of cognitive development as defined by Piagetian theory, for example) and demonstrate that the characteristic is correlated with success in physics. Then, typically, instruction is modified to take into account student inadequacies with respect to this characteristic, and studies are conducted to demonstrate that student achievement improves. However, this research strategy has produced limited results, as Mallinson (1977), Peterson (1979), and other commentators have pointed out.

The instructional research effort to be described in this paper represents an alternative approach to the design of instruction. Central to this process of instructional design is the analysis of traditional instructional tasks for the purpose of specifying the underlying cognitive processes and structures that are necessary for the successful completion of the task. The specification of these processes and structures for physics problem solution represents an important part of the recent empirical findings of cognitive science research.

Research Background

Cognitive analysis of the instructional problem

Recent developments in cognitive theory have important implications for the design of physics instruction. We will describe (1) how the theory helps us to gain insight into probable causes of the observed difficulty students have in learning to apply Newton's

Laws to the analysis and description of physical situations and problems involving forces and motion and (2) how the theory is a basis for generating hypotheses about possible features of instruction that will more effectively produce the desired learning. Two lines of research that are particularly relevant to the cognitive analysis of the instructional problem are those concerned with problem solving and semantic memory.

Researchers in the domain of problem solving are concerned with both the processes and structures that problem solvers are observed to apply in the successful solution of problems (e.g. Greeno, 1978; Newell & Simon, 1972). The solution of physics problems requires both the availability of these general problem solving strategies and the understanding of physical situations which are observed directly or described in the text of the problem. Current theories of semantic memory and natural language understanding (Anderson, 1976; Anderson, Reynolds, Schallert & Goetz, 1977; Bransford & McCarrell, 1974; Kintsch, 1974; Lindsay & Norman, 1972; Norman & Rumelhart, 1975; Quillian, 1968; Shank, 1972; Winograd, 1972) tie the existence of relevant schemata to the process of making inferences and coming to understand a situation. In the context of physics, understanding implies the construction of mental representations of physical situations that include the objects that are a part of the physical situation, the concepts and scientific principles that are relevant to the situation, and the relationships that exist between objects, concepts and principles (Winograd, 1972). Essential to the construction of a mental representation is the process of inference.

Making valid inferences is dependent on schemata that are relevant, correct and complete. Thus, understanding physical situations as physicists understand them requires both that the relevant schema is present and that the features of the physical situation evoke the schema.

Given this brief description of the intersection of the theories of problem solving and understanding, we will examine in some detail specific aspects of these theories that are relevant to mechanics instruction in the middle school. Cognitive analyses of the processes and structures required for mathematics and physics problem solving clearly demonstrate the relationship between successful problem solution and the presence of relevant schemata (Chi, Feltovich & Glaser, 1979; Heller & Greeno, 1978a; Hinsley, Hayes & Simon, 1977; Larkin, 1979; Larkin, McDermott, Simon & Simon, 1980; McCloskey, Caramazza & Green, 1980; Simon & Simon, 1978). Heller and Greeno (1978b) and Riley and Robinson (1980) have identified and specified in a formal way three schemata that characterize addition and subtraction word problems that appear in several arithmetic text series and on standardized tests. These models have served as a basis for specifying a developmental continuum for less to more skilled performance of problems of this type. Such analyses can be applied to the specification of instructional tasks appropriate at specific points along such a learning continuum.

Physics problem schemata. Schemata for physics problems do not exist at the same level of specificity as those for arithmetic word problems. However, recent work by Chi et al. (in press) describes

explicit differences in the physics problem schemata of experts and novices. When asked to sort college level physics problems from Halliday and Resnick (1974), novices sort on the basis of the problem's surface structure (objects such as springs and inclined planes; terms such as friction; and similarities of diagram associated with the problem). Experts sort the problems on the basis of the problems' deep structure---physical laws (e.g., energy conservation principles or Newton's Laws) that are not mentioned specifically in the problem. This is taken as evidence that experts transform the surface features of the problems into a more abstract representation which includes the scientific principles required for the successful solution of the problem. A replication of this experiment verified that the problem schemata of novices are object-oriented, while the schemata of experts are principle-oriented. Included in this study were some advanced novices who sorted problems on the basis of principles but mentioned surface features of the problems when rationalizing their sorts. This finding suggests a continuum along the dimension of object-oriented to principle-oriented schemata. The finding is also consistent with the view that novices are, in part, characterized by having a number of different schemata which may be applied to, say, situations involving motion, while experts, are, in part, characterized by having a single schema for such situations -- one based on Newton's Laws. This suggests that the process of moving from novice to expert involves, in part, the collapse of and integration of multiple schemata into a single schema. Such an interpretation allows more ready incorporation of the

phenomenon (observed in other studies considered below) of novices switching from an Aristotelian schema to a Newtonian schema, and back again, as they move from one situation involving force and motion to another.

In another experiment in the Chi et al. study, subjects were asked to elaborate on the concepts and problem features that had been used as a basis for categorization of the problems. The analysis of these data indicates that the novices have the same information about the physical principles as the experts, but novices fail to link objects and concepts with physical principles because the necessary relations between these elements are lacking. In contrast, for the expert the description of a physical situation immediately evokes an applicable physical principle. This suggests that the expert has information relating to conditions under which the principle is applicable and this information is associated with the principle. Further, there is evidence that the expert's knowledge is organized hierarchically along the dimension of abstractness, a characteristic which allows for either bottom-up or top-down processing. The novice's less-integrated structure does not allow for such flexible accessibility.

The purpose of the fourth experiment in the Chi et al. study was to determine the features of the problems on which the experts based their selection of the appropriate physical principle for solution of the problem. The results of the experiment reveal a significant difference in the degree of abstractness of the expert and novice representations of problem types and features. Experts immediately

abstract a basic solution strategy from the surface features of the problem. In contrast, novices do not distinguish between the plan for the solution of the specific problem and the existence of a general solution plan for the problem type. Further, the form of the features mentioned by the experts differ from the form of the features mentioned by the novices. Experts mention transformed or abstracted features while the novices describe the specific objects and physical constructs. This suggests that the expert translates the literal objects and conditions of the problem into canonical objects and, on the basis of this representation, selects the prototypical problem type of which the particular problem is a specific example. Expert's relevant features contain reference to the states, conditions and changes in states and conditions. Novices do not mention these features, suggesting either that their schemata for the problem type does not contain a change of state or condition subschema, or that appropriate relations linking schemata to problem representations do not exist.

In summary, the Chi et al. study concludes that the following differences characterize schemata that expert and novice physicists apply in the solution of physics problems: (1) The problem-type schemata of experts are based on physical principles (for example, energy conservation and Newton's second law) and those of novices are based on physical objects (for example, springs and inclined planes) and constructs (for example, friction and gravity). (2) The contents of the schemata of experts and novices do not differ significantly in information content; however, the novices' structures lack important

relations, specifically relations between the surface features of the problem and the scientific principles which are the basis for solutions. (3) Experts translate surface features of the problems into canonical objects, states, and constructs while the novices represent the problem in terms of the literal objects and constructs described in the text of the problem. (4) Links exist in the expert's representations of knowledge structures between the abstract representation of features of the problems and the physical principles which are the basis for the solution of the problem. (5) Experts' schemata are arranged hierarchically along the dimension of abstractness; in contrast, the different levels of the novices' knowledge are not well integrated, thus preventing easy access from one level of abstraction to another.

The descriptions of physics problem schemata provided by the Chi et al. study do not provide as complete and as formal models of the knowledge structures required for the solution of intermediate level mechanics problems as do arithmetic story problem schemata modeled by Heller and Greeno (1978a). However, they do, we believe, provide sufficient specification of knowledge structures to facilitate the design of exemplary introductory physics instruction. For specification of the process requirements for such instruction, we now consider the cognitive research on problem solving processes.

Problem solving processes. Cognitive research on problem solving has generated detailed specifications of problem solving strategies for many categories of problems (Newell & Simon, 1972 ; Greeno, 1978; Larkin, 1979). One finding from this research that is particularly

pertinent to the instruction we propose is reported by Larkin. Her analyses of thinking-aloud protocols indicate that expert physicists perform a preliminary qualitative analysis before proposing equations for the quantitative solution of the problem. In contrast, novices immediately begin the search for an equation and proceed to match the information presented in the problem with terms in the equation. This processing difference is diagrammed in simple form in Figure 1.

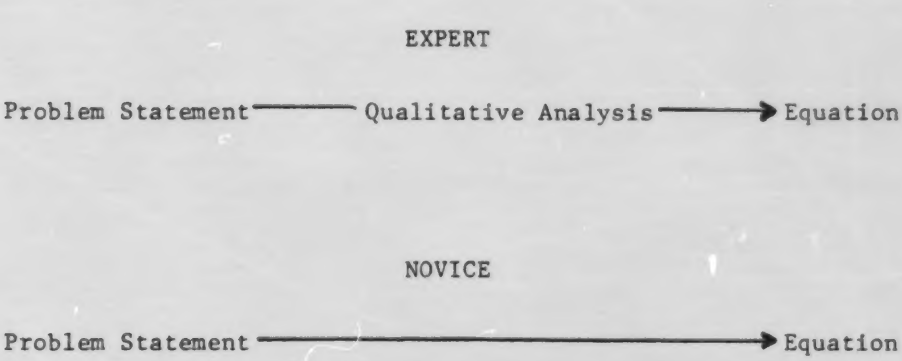


Figure 1

Expert's and Novice's Problem Solving Strategies

This important difference between experts and novices has, we believe, significant implications for introductory physics instruction.

Since so much of students' time learning physics is spent solving problems, the results of a cognitive analysis of physics problems provide a basis from which we can infer the objectives of physics instruction and specify them in a highly detailed fashion (Greeno, 1976). These detailed specifications of the knowledge and processes that are the instructional objectives for classical mechanics can be

used to facilitate the design of instruction. Assuming that a detailed description of the initial cognitive state of the learner is available, the process of making a detailed match of the features of the desired cognitive state against the learner's initial cognitive state provides an explicit and complete description of the changes in cognitive state the instruction must provide. For each type of discrepancy between the initial and desired cognitive states, appropriate instructional strategies are specified by logical analysis and consideration of relevant theories of learning. This list of instructional strategies is a useful tool for the analysis of instructional practice and for further instructional research.

Cognitive state of beginning physics students

In the specific instance of beginning physics instruction, results from empirical studies exist that allow us to specify in considerable detail the learner's initial cognitive state. The findings from this research consistently demonstrate that prior to formal physics instruction most young people (and many uninstructed adults) have a conception of motion that is more Aristotelian than Newtonian (Champagne, Klopfer, Solomon & Cahn, 1980; Driver, 1973; Driver & Easley, 1978; Leboutet-Barrell, 1976; Singer & Benassi, 1981). Other research findings show that remnants of the Aristotelian conception persist with many "successful" physics students, that is, with students receiving high grades in introductory physics courses (Champagne, Klopfer & Anderson, 1980; Gunstone and White, in press). This research provides empirical support for what physics teachers

have long observed, namely, that traditional instruction does not facilitate an appropriate reconciliation of preinstructional schemata with the content of instruction. These observations are consistent with findings emerging from cognitive psychology that demonstrates the impact of existing knowledge in memory on the comprehension of text. (Lindsay & Norman, 1972; Bransford & McCarrell, 1974; Anderson, Reynolds, Schallert & Goetz, 1977).

This research demonstrates that all incoming stimuli which are remembered are subject to reorganization by the learner. The incoming stimuli are primarily restructured by the learner in terms of the learner's own past experiences, and only secondarily in terms of the organizing principles of the material itself (Lindsay & Norman, 1972). Insight into the nature of the structure has been obtained through experiments where some verbal information in either written or auditory form is presented to individuals who are then asked to recall exactly what was read or heard and to select from choices an exact match to previously presented material. Results of this research provide evidence that: (1) if the verbal material is understood, subjects can recall more of it than if it is not understood; (2) subjects who understand the verbal material have reorganized it in memory. An interpretation suggested by these results is: "The memory system encodes the meaning of the material that has been experienced, not the material itself. Man attempts to understand rather than remember (Lindsay & Norman, 1972, p. 428)."

According to this interpretation, students engage in active, meaningful structuring of text they read and lectures they hear in

order to remember and understand incoming information. The issue then becomes: "What are the principles that determine the effectiveness and efficiency of active structuring?" The results of cognitive research suggest that the primary determinant is the structure of the information. Generally, the more closely a learner's structured representation of information in memory matches that of an expert in the field, the more the learner is said to understand about that field (Lindsay & Norman, 1972). Thus, an interpretation of the primary goal of instruction is to provide learners with the skills and experiences that enable them to construct mental representations of information which closely approximate that of the expert. If, however, the learner lacks relevant prior experience, the learner's memory of information will not resemble the expert's structure.

The issue of memory structure is of prime importance to the comprehension of instruction. The organization of information in memory reflects the learner's level of understanding of that information. Given that some reorganization of information must occur, an important question is the degree to which the organization in memory is congruent with the original organizing principles of the instructional material. Research that will be discussed below indicates that this congruence is primarily a function of the degree to which the learner's previous knowledge and experiences match those of the writer or speaker.

Cognitive psychologists have studied ways in which prior semantic knowledge influences comprehension of verbal materials. The early studies in the area of reading comprehension aimed at demonstrating

that something other than the linguistic structure of a sentence is required to explain a person's comprehension of that sentence. The "something other" is described as the person's world knowledge and then is characterized as a "schema," "plan," "script," etc., and some of its characteristic relations to linguistic input are investigated. In general, studies of text comprehension indicate the facilitative effect of schemata or world knowledge. Studies of science learning, reviewed by Driver and Easley (1978), indicate that world knowledge may be logically antagonistic to science content and may persist after science instruction.

Bransford and McCarrell (1974) review studies which indicate that the process of understanding text involves creation of "semantic descriptions" that use both the reader's world knowledge and the sentence input. In this research, the contexts for interpretation of text either were common world knowledge or were induced by the experimenter. Anderson, Reynolds, Schallert & Goetz, (1977) indicate that an individual's "private" representation of the world can affect text comprehension. Anderson et al. presented two ambiguously-worded stories to groups differing in backgrounds and interests. After reading each story, subjects answered factual questions about it. Several instructionally interesting points emerged. First, subjects read the story that could be interpreted through their academic interests as though it was about their own academic area, and they read the other story in its more general sense. Second, subjects who read stories that matched their academic backgrounds were not aware of the possibility of another interpretation of the story. Third,

subjects' responses to most of the factual questions did not make explicit their interpretation of the story. The authors suggest that teachers should be aware of the possibility that a student's apparently correct answer could actually be conceptually incorrect and sufficiently ambiguous to permit the teacher to apply the correct conceptual schema to its interpretation.

Forming knowledge links. One factor contributing to the strong relationship between the learner's prior knowledge and the quality of learning from instruction is the process of linking incoming information to existing knowledge. When links are formed in a way that gives meaning and structure to the incoming information, learniing is likely to proceed quite smoothly. However, when a learner has very little relevant existing knowledge to link with the new information, learning difficulties should be expected. This interpretation is consistent with the theory that human learning is an active constructive process, and it stands in contrast to a theory that assumes that the learner is a passive vessel that receives and stores the information exactly as it is presented. As previously discussed, current thinking in cognitive psychology favors an active constructionist theory, and most research in cognitive science today is conducted within that theoretical framework.

The optimum organization for instructional materials is one which enables the learner to form the appropriate links with previous learning. When information is presented without directly linking it to the learner's existing cognitive structure, misunderstanding and an inability to recall the information will result.

In general, research has demonstrated that world knowledge has a facilitative effect on comprehension. However the science learning studies reviewed by Driver and Easley (1978) lead one to suspect that facilitation is not the whole story. A study by Leboutet-Barrell (1976) indicates that high school and college students have misconceptions about force and motion which persist despite instruction. The misconceptions are described as pre-Galilean. In a study by Cole and Raven (1969) with 12 to 15 year-olds, it was necessary to give the students "opportunities to reject irrelevant factors in understanding the principle of flotation." Rowell and Dawson (1977) also explicitly considered common misconceptions when designing instruction on the law of floating. Despite efforts to refute misconceptions in instruction, some misconceptions persisted. Instructional work by Fleshner (1963) in the Soviet Union indicates that students' intuitive ideas may co-exist with ideas derived from instruction. In a study by Driver (1973), 11 and 12 year-old pupils were interviewed prior to, during, and after instruction on several topics of a physical science course. Alternative theoretical frameworks to explain observations were identified and used during the instruction. Driver reports that counter-examples and conflicting evidence did not produce a change in pupils' thinking. Alternative theories were learned at the verbal level only.

Comprehension of science experiments. Our own work in science (Champagne et al., 1980a, 1980b) has demonstrated that prior knowledge affects students' comprehension of science instruction, specifically, the students' comprehension of science experiments. We have been

particularly interested in the difficulty that beginning physics students have in learning classical mechanics. Our research has demonstrated that it is not the students' lack of prior knowledge that makes the learning of this topic so difficult but rather the fact that they come to instruction with well-formed notions about the motion of objects --- notions that have been reinforced by their experiences. However, the notions they may have stand in contradiction to the tenets of classical physics, and these notions tend to interfere with or inhibit the learning of mechanics.

The problem is compounded by the fact that many of the terms used in classical mechanics are used in everyday life --- terms such as acceleration, momentum, speed, and force. The meanings of these terms as used by physicists are quite different from the way in which they are used in everyday life. Thus we observe that students misunderstand physics instruction because they interpret their physics lectures and texts in the context of their idiosyncratic understanding of the terms rather than in the way in which the text or teacher is using the terms. A first goal of our work is to specify in detail the semantic knowledge students bring to science instruction. Toward this end we have devised a series of tasks in which (1) some simple physical apparatus and a manipulation of it are described; (2) the students are asked (a) to predict the outcome of the demonstration and (b) to report the information they used to generate the prediction; (3) the demonstration is then done and the students are asked to describe their observations and to discuss any conflicts between their predictions and their observations.

In one task the students are asked to compare the times for two objects to fall equal distances. The objects are the same shape and size but differ in mass. This task has been administered to several groups of academically talented adolescents (7th and 8th graders) and to beginning college physics students. The results demonstrate ways in which students' conceptions influence (1) their understanding of science texts and lectures, (2) their observations, and (3) their interpretations of their observations. Sometimes the influence of the students' conceptions is to inhibit their understanding or distort their observations and interpretations. An example from the students' written protocols illustrates the interactions between the students' conception of falling objects and their interpretation of text or lecture. A significant number of the college and middle-school students predict that the heavier object will fall faster and justify the prediction by stating that Galileo proved the general principle that heavier objects fall faster. To support their contention many describe an experiment that they believe Galileo performed - dropping a feather and a gold coin - and note that Galileo asserted that the coin falls faster, thus demonstrating that Galileo proved that heavier objects fall faster. We infer this to mean that the students have been exposed to some of Galileo's work, either by reading or hearing about it. However, if we compare the generally accepted account of Galileo's argument with the students' interpretation, we note significant differences. Galileo used a thought experiment to support his assertion that when air resistance is controlled for, the heavier object and the lighter object will fall at the same rate. Galileo's

complete argument is that: if a feather and a coin are dropped in air, the coin will fall faster; if, however, the objects are dropped in a vacuum the effects of the upward push of the air will be negated and both objects will be observed to fall at the same rate. It is our observation that some students who predict that heavier objects fall faster remember the part of Galileo's experiment that is consistent with their prediction and forget the part of the experiment that is inconsistent with their prediction.

There is also evidence that students' observations tend to be consistent with their predictions. In some cases protocols clearly indicate that the student's observation is in conflict with his prediction. In these cases the student often hedges in his observation. For example one student predicted that the heavier object would fall faster and wrote in his observations that indeed the heavier one had fallen faster but expressed surprise that the speeds were so nearly the same.

Our observations of the students, both immediately after the administration of the falling objects task and for about eight weeks following during instruction, supports the hypothesis that the students' interpretations of science experiments are influenced by their beliefs about the relationships between an object's mass and its speed in free fall. When the administration of the task was completed, one group of students was told that they could experiment on their own with equipment, including that used in the demonstration. Several students did so. One student weighed the two blocks. He had predicted that the metal block would fall faster than the plastic

block, but his observations contradicted his prediction based on the belief that heavier objects fall faster. To resolve this contradiction, he reasoned that, despite the difference in the materials from which the two blocks were made, they must be the same weight because they fell at the same rate. He proceeded to test this hypothesis by weighing the two blocks.

Two other students (Tammy and Mary) who also predicted that the heavier object falls faster, experimented by dropping the blocks from a greater distance above the floor than the demonstrator had dropped them from. Tammy climbed onto a table and dropped the blocks while Mary put her head on the floor to hear when they struck the floor. These students reasoned that the blocks had, in fact, fallen at different rates, but that the difference in descent times was too small to be observed over the short distance (approximately one meter) used in the original demonstration. They tested this hypothesis by designing an experiment which used a more sensitive procedure, i.e, dropping the blocks from a greater height, to illuminate any difference in the blocks' rates of fall.

The students' continuing concern with the problem of objects which differ in mass falling at the same rate also was evident in discussions of experiments the students designed throughout the eight weeks of instruction. At one point during a class discussion, all the students agreed that two carts of unequal mass, but equal volume, would strike the ground at the same instant when dropped from the same height. When they were asked how the speed of the carts would compare if the carts were rolled down an inclined plane, only one, Nick,

argued that the velocities would be the same. The other students decided to convince Nick that he was in error by doing a demonstration. The students' first attempt was to do the demonstration by tilting the table and sliding objects down it. However, frictional forces were obviously present, so the students switched to rolling objects down the inclined table. This was followed by letting a rider carrying different weights slide along a tilted air track. Their principal concern was to demonstrate that the velocity of an object on an incline depends on the mass of the object. This belief is logically consistent with the belief that the velocity of an object in free fall depends on its mass. The students' pre-instructional belief continued throughout the instruction period to prevent them from learning that the free-fall velocity is independent of mass.

The observations in the demonstration for the task with two falling objects of different mass were often questioned. Some of the students continued to argue that they failed to observe differences in the rates of fall because of the insensitivity of the experimental procedure. Their experiments were designed to demonstrate differences in the rate of free fall. This was to be accomplished by increasing the sensitivity of the experimental procedures by increasing the distance through which the objects dropped. They also placed their heads on the floor and either sighted along the floor or listened for the impact in order to better distinguish between times of impact. It must be remembered that these experiments, far from being idle exercises for the students, reflected a real dilemma that they faced.

The students' Aristotle-like conceptions that the greater downward force applied to the heavier object implies that its speed of fall must be greater are incompatible with the observation that the objects fall at the same rate. One way to resolve this dilemma is to design experiments which will discredit that observation. A discredited observation doesn't act as a challenge to the students' pre-instructional conceptions, which they are reluctant to change anyway.

Other research we have conducted (Champagne et al., 1980a) demonstrates that the belief that heavier objects fall faster than lighter objects is not easily changed by instruction, thus demonstrating the strong influence that prior knowledge has on the effectiveness of instruction --- in this case the prior knowledge having an inhibiting effect on learning. In a study of beginning college physics students, about four students in five believed that, all other things being equal, heavier objects fall faster than lighter ones. These results were particularly surprising since about 70% of the students in the sample had studied high school physics, some for two years. A chi-square test showed that students in the sample who had studied high school physics did not score significantly better than those who had not. This finding has been replicated in follow-up studies.

In a report of a similar study of the knowledge of gravity possessed by beginning first-year physics students at Monash University, all of whom had successfully completed two years of high school physics, Gunstone and White (in press) conclude: (1)

"...students know a lot of physics but do not relate it to the everyday world;" and (2) "In many instances the students used mathematical equations to explain predictions, though often inappropriately, which indicates that they had lots of physics knowledge to hand but were unskilled in seeing which bit applied to the given situation (p. 15)." In their conclusions, Gunstone and White note as evidence of the students' disinclination or inability to link physics knowledge to the real world the "widespread errors of scale in estimating the effects of friction and air resistance and the relation between height and gravitational field strength, in the minimum number who used experience to support their prediction in Situation B, [the analysis of the effects of mass on speed in free fall] and in the large number who related the pulley system incorrectly to see-saws, beam balances and the like (p. 15)." They conclude: "...much more attention may have to be given to integrating the knowledge acquired in school to general knowledge (p. 15)."

Modifying students' cognitive states. The results of these studies based on the responses of students with one or even two years of formal instruction in high school physics are remarkable in themselves, but when considered in conjunction with the research contrasting physics problem solving performance of experts and novices, they suggest several interesting implications for further research and for instruction. It is clear that students generally do not learn to relate their physics knowledge to the real world as the result of either high school or beginning college physics instruction. Based on a cursory analysis of physics texts and our knowledge of

physics instruction, we conclude that this skill is seldom, if ever, taught explicitly. Two interesting theoretical questions are: How does this skill of relating physics knowledge to real-world phenomena become incorporates into the problem solving repertoire of physics experts? Is it possible to instruct students in such a way that the skill will become a part of their novice problem-solver repertoire?

Given that the skills and knowledge applied by experts in the qualitative analysis of physical situations are cognitive objectives of physics instruction; that explicit instruction in the knowledge and skills required for successful performance is not now a part of physics instruction; and that part of such instruction must focus on producing a schema change in students which results in the incorporation and integration of physics principles and interpretations of real world phenomena; the question then becomes: How do these skills and knowledge structures develop in experts?

For the purpose of this discussion, we consider three factors that differentiate the experiences of experts; from the experiences of novices; these are: (1) additional formal instruction, (2) more extensive practice in solving problems, and (3) more extensive verbal interactions about physics. The Chi et al. (in press) study suggests that the contents of novices' data structures for particular types of physics problems are similar to those of experts with respect to objects, concepts, and terms; however, experts' data structures contain many more linkages. The more extensive data base, which experts acquire as a result of their greater exposure to formal instruction, is not necessary for the successful solution of problems

of the type on which the analysis of expert-novice differences is based and, therefore, is not part of the cognitive objectives for the beginning level physics instruction. However, the links in experts' knowledge structures which we hypothesize develop as a result of extensive practice in problem solving are cognitive objectives of beginning physics instruction. The development of these links may be facilitated by verbal interactions.

A significant difference between physics experiences of experts and novices is that experts have had experiences which require either verbal interactions with others or the organization of physics information for the purpose of communicating it to others. We hypothesize that this type of experience is important to schema change. The instructional question then becomes: Can explicit instruction that incorporates extensive verbal interaction supplant the effects of extensive practice in solving problems? Anderson (1977) suggests that one type of verbal interaction, namely, Socratic dialogue, is a possible mechanism for schema change. Thus, engaging in Socratic dialogue (or instructional dialogue, a term we prefer because of the multitude of meanings attached to Socratic dialogue in the literature) may have an effect on building relations in schemata that parallels the effect of extensive practice in problem solving.

The processes by which new schemata develop or existing schemata are modified are just beginning to be understood (Greeno, 1980). Information processing models of schema development generally have not gone beyond the level of describing stages. Nonetheless, several valuable ideas concerning the development of schemata and suggestions

for modifying schemata have been offered.

Two principal mechanisms for schema acquisition and modification have been discussed by Rumelhart and Ortony (1977). Each mechanism is, in a sense, the antithesis of the other. Specialization occurs in a schema when one or more of its variables are fixed to form a less abstract schema. Conversely, generalization occurs in a schema when some fixed portion is replaced by a variable to form a more abstract schema. The generalization mechanism can readily be seen to be applicable, for example, in a motion-of-objects schema. As we have observed in our work with middle-school students, the uninstructed student has the motion schema: A PUSH PRODUCES MOTION. As a result of appropriate instructional experiences, the student's motion schema could become: A FORCE PRODUCES ACCELERATION. The fixed portion, PUSH, in the initial schema has been replaced by a more general variable, FORCE, which can take on several values in addition to PUSH. Similarly, the general variable, ACCELERATION, which can have different values, has replaced the initial schema's fixed portion, MOTION. The modified schema is considerably more abstract and, hence, has a much broader range of applicability. The schema has been brought to this advanced stage through the straightforward operation of the generalization mechanism.

While the gradual growth and modification of schemata doubtless occur via such mechanisms as generalization and specialization, it has been suggested that for highly integrated schemata more dramatic changes, amounting essentially to a shift to a new paradigm (in Kuhn's (1962) sense), must also take place. To bring about schema change on

such a large scale, a dialectical process appears to be necessary. Riegel (1973) points out that the thinking of both adults and children is dialectical, and he proposes that dialectics is "the transformational key" in cognitive development. Anderson (1977) suggests that "...the likelihood of schema change is maximized when a person recognizes a difficulty in his current position and comes to see that the difficulty can be handled within a different schema (p. 427)." As the mechanism for promoting dialectics in the classroom, Anderson advocates the use of a Socratic teaching method. By participating in the dialogues which occur in Socratic teaching the student is forced to deal with counterexamples to proposals and to face contradictions in his or her ideas. To overcome the attacks of adversaries in the dialogues, the student must construct a new framework of ideas that will stand up to criticism. This newly constructed framework constitutes a schema change. From such analyses of Socratic teaching methods, and from analyses by Collins (1977) and Collins and Stevens (in press), various types of questions have been identified for use in instruction to help bring about a change in the student's schema

Changing Motion-of-Objects Schemata

Goal states

In the preceding discussion, two basic issues involving the learning of physics of beginning students have been explored. These are, first, the differences between novices and experts in their approach to the solution of physics problems and, second, the extent

to which novices retain and use schemata derived from experience in the real world, even when they also retain and use conflicting schemata derived from physics instruction. The first of these differences was represented in Figure 1 above. In Figure 2, a simple view of the impact of both of the novice-expert differences on the solution of problems is shown. The case of motion-of-objects problems is used in this example, which indicates the clear advantage of the expert's comprehensive schema in the problem solution process. Another apparent advantage is the expert's employment of a qualitative analysis. If beginning physics students were to become skillful in using a qualitative analysis, they might be able to solve problems with the approximate facility of the expert. In that case, both the development of skill in the qualitative analysis of mechanics problems and modification of students' motion-of-objects schemata so that they reflect significant characteristics of the expert's schema would appear to be worthy goals of beginning physics instruction.

In the following major section, we shall describe and discuss an instructional strategy whose purpose is to enable students to attain these goals. Then, we propose research which will test the hypothesis that application of instructional dialogue in the context of the qualitative analysis of mechanics problems will produce changes in the motion-of-objects schemata of beginning physics students. Detailed descriptions of the changes will be specified in terms of the knowledge structures of experts in the domain. These descriptions, assembled from the empirical studies of physics problem solving, specify the cognitive goal states that are to be approximated by

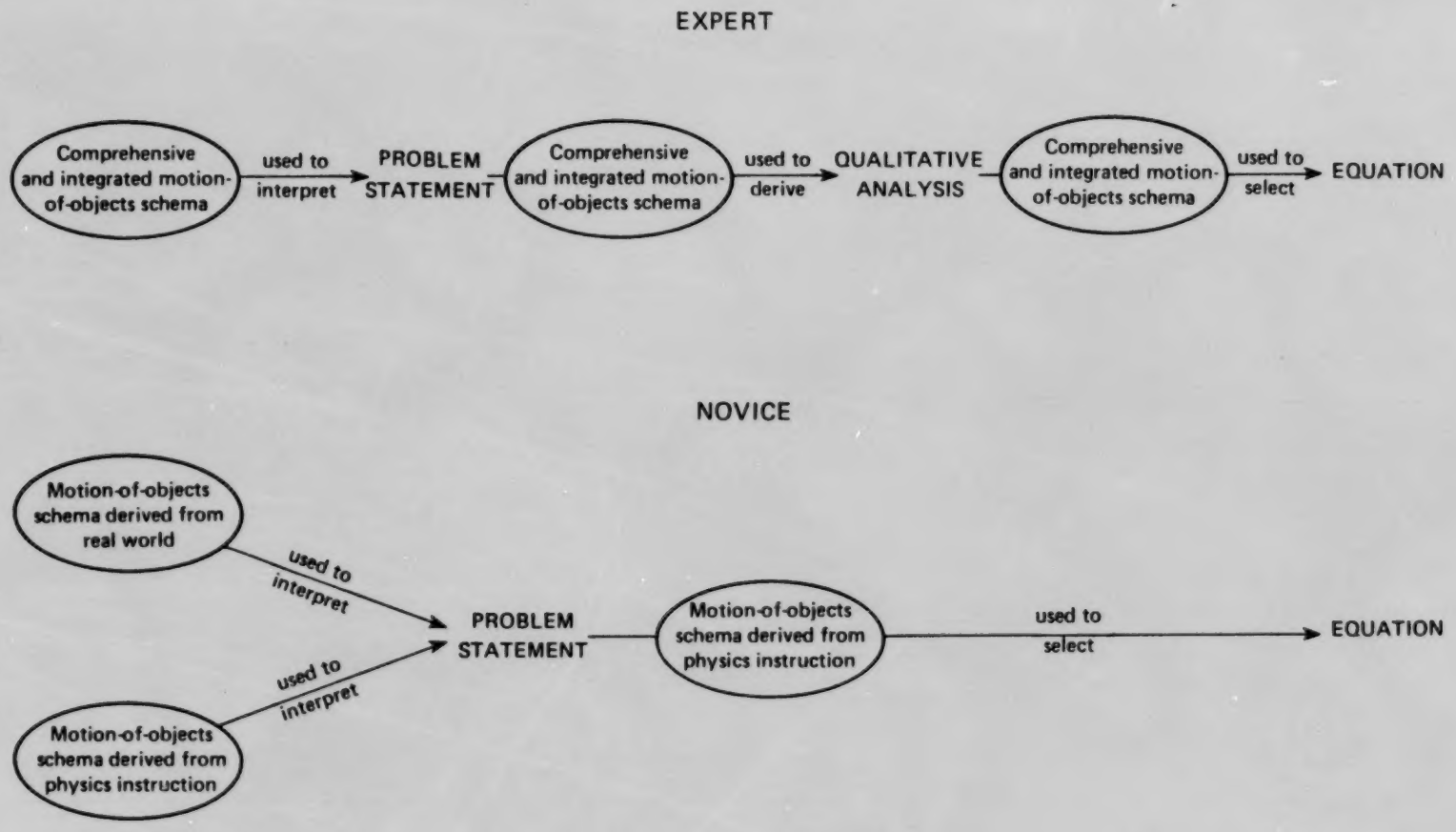


Figure 2. Problem solving strategies and schemata of Expert and Novice.

students as the result of their instructional experiences.

Beginning students' schemata.

The specifications of the features of the schemata of the beginning students are also empirically based. From our analysis of empirical studies investigating students' preinstructional conceptions of the causes of motion of objects, we conclude that the following are characteristic of the explanatory schemata of beginning physics students:

(1) Concepts are poorly differentiated. For example, students use the terms speed, velocity and acceleration interchangeably; thus, the typical student does not perceive any difference between two propositions such as these -- (i) The speed of an object is proportional to the [net] force on the object; (ii) The acceleration of an object is proportional to the [net] force on the object.

(2) Propositions are imprecise and the imprecision derives from differing sources.

(a) Some of the imprecision of propositions is attributable to the meanings students have for technical concepts which are different from the canonical meaning. Example: More force means more speed.

(b) Other imprecision can be interpreted as errors of scale (Gunstone & White, in press). Example: Gravity pulls harder on objects that are closer to the earth. (This proposition, in the context of an object falling a distance of three meters, is correct only in theory because the

difference in the force of gravity (approximately 1 part in 10^{13}) is too small to measure. If, however, the difference in distance from the earth were large (several hundred kilometers), the difference in the force of gravity is significant.)

(c) Other propositions are just wrong and may arise because of students' attempts to inappropriately formulate general rules of motion from their experiences in the real world. Example: Heavy objects fall faster than lighter objects.

(3) Explanatory schema are sitution-specific, thus suggesting that there is no naive abstract representation extant in the schemata that makes the schemata applicable to large number of physical situations.

This last characteristic was exemplified in our own work with middle-school students. We have observed that, given four physical situations, all of which could be explained by using Newton's Second Law ($F = ma$), students never give any indication that they perceive that a common explanatory system might be applied to all four of the situations. In fact they never notice that a proposition they have used to explain the motion in one of the situations is directly contradicted by a proposition they use to explain the motion in another situation. This suggests that they are unaware of any need for consistency across situations. For example, as previously described, students do not recognize that the same physical laws apply to objects in free fall and to objects sliding down an inclined plane. At one point during a discussion all the students agreed that two

carts of unequal mass, but equal volume, would strike the ground at approximately the same time when dropped from the same height. When they were asked to compare the times for the carts to slide down an incline, however, only one of them argued that the times would be about the same.

Instruction in Qualitative Analysis of Physics Problems

Illustrations of schema change

Empirically-based information about physics problem solving strategies and schemata of uninstructed students, novices, and experts is summarized in Table 1. Although this summary table cannot display all the nuances associated with the strategies and schemata, its lower portion does make evident the contrasts and similarities in the characteristics of the three groups' schemata with respect to principles, surface features, and second-order features, each of which is briefly explained in the first column. The second column in the table describes current conceptions of the characteristics of physics schemata of the uninstructed students with whom we shall be working. The fourth column describes characteristics of the experts' schemata, characteristics which represent the cognitive goal states that we seek to approximate as a result of instruction. By comparing the characteristics of the uninstructed students' and experts' schemata, the nature of the needed changes in the students' schemata can be specified. It should be emphasized that, with our proposed instructional strategy we do not expect the students' schemata to pass

Table 1

Problem Solving Strategies and Schemata of Uninstructed Students, Novices, and Experts

PROBLEM SOLVING STRATEGIES

UNINSTRUCTED STUDENTS	The typical procedure for solving problems is to find a general rule which appears to cover the physical situation described in the problem, and then to use the relationship described in the identified rule deductively to derive an answer to the problem. Rules to be employed in this process may be recalled from experiences with similar physical situations, or they may be recollections of authoritative statements from books or people.
NOVICES	The principal procedure for solving problems is to instantiate variables in equations. This procedure may be chained through a series of equations. Abstracted solution methods are lacking.
EXPERTS	Associated with the organizing schema are its specific conditions of applicability and the necessary problem solution methods. Experts abstract a basic solution strategy from the surface features of the problem and engage in quanitative analysis of the problem prior to determining a quantitative solution.

SCHEMATA

FEATURES OF SCHEMATA	CHARACTERISTICS OF UNINSTRUCTED STUDENTS' SCHEMATA	CHARACTERISTICS OF NOVICES' SCHEMATA	CHARACTERISTICS OF EXPERTS' SCHEMATA
PRINCIPLES Ideas of some degree of generality that express relationships; principles are applied to solving problems; can serve to organize schemata.	Principles are generalized rules derived from everyday experiences (world knowledge). They are imprecise propositions. The imprecision is due to vagueness about the meaning of concepts, errors of scale, and inappropriate formulations of general rules. The principles (rules) have limited scope and tend to be situation-specific. The notion that an abstract principle can apply to a range of different physical situations is lacking or poorly developed. There appears to be no awareness of the need for consistency along the rules that cover different physical situations.	Principles are relationships between physical variables expressed as equations or rules. Some of the principles are the major physical laws expressed in equation form, but there is no evidence that they serve as organizers of schemata.	Principles are major physical laws, which are highly abstract and express relationships of great generality. Included with each principle are the conditions under which the principle applies. Each principle has an associated schema, which is oriented by the content and applicability conditions of the principle. The applicability conditions usually are expressed in terms of second-order features.

(Table 1 continued)

(Table 1 continued)

FEATURES OF SCHEMATA	CHARACTERISTICS OF UNINSTRUCTED STUDENTS' SCHEMATA	CHARACTERISTICS OF NOVICES' SCHEMATA	CHARACTERISTICS OF EXPERTS' SCHEMATA
OBJECTS AND PHYSICAL CONDITIONS (SURFACE FEATURES) Physical objects and conditions described or presented in a problem situation; physical features of objects and their states of motion or position that are directly perceivable from verbal description; diagrams or direct observation of the physical situation.	Concrete objects and the directly observable properties of objects are present. A reasonable inference is that the objects and properties define the specific physical situation which, in turn, directs the search in memory for a general rule that covers it.	Physical objects and their surface features are the basis for categorizing problems. It is inferred that an object or a configuration of objects functions as the organizing element (node) in its schema for the problem. The content of the representations may be concrete objects or abstractions at the level of diagrams.	Concrete objects, their physical configurations, and diagrams of objects are present in the schemata, but none of these if prominent. It is inferred that objects serve primarily as vehicles for identifying second-order features, and that sometimes they trigger the activation of a particular principle-based schema.
PHYSICS CONCEPTS AND SYMBOLS (SECOND–ORDER FEATURES) Idealizations of physical objects (e.g., an elephant is represented as a point mass), and constructs or entities (e.g., energy, force); conventional representations of physical entities (e.g., vector components).	There is no evidence that second-order features are represented in these schemata. Concepts and terms are present, but many are poorly differentiated. The meanings of the terms are their real-world meanings, rather than their technical meanings in physics.	Some conventional representations of physical entities are present, and idealizations of physical objects may be used in problem representations. Concepts and terms related to the objects which dominate the problem-solution schema are present. Novices report taking terms directly from the problem statement to identify equations that could be approximately employed in solving the problem.	Representations of physical objects in their idealized form are prominent, with the content of the representations determined by the organizing schema. Physical entities are represented according to the conventions of the field. Features abstracted from the problem statement are also present. Some experts report that these features help to select the basic approach to problem solutions, thus indicating direct links between these second order features and principles. Concepts relevant to the organizing schema are present. Associated with each concept are its interconnections of relations with other concepts and with the schema's major physical law.

through a transition stage showing all the characteristics of the novices' schemata described in the third column of Table 1. Specifically, the instruction we propose will enable the beginning student to engage in the qualitative analysis of physics problems and thereby encourage the reconciliation and integration of the student's existing schema developed from real world experiences with the schema developed as a result of formal physics instruction. Thus, the creation of the conflicting schemata observed in many novices is avoided.

Specific changes we anticipate in students' schemata are described through an illustration using representative problems. Figure 3 displays three such problems. The first problem is to make a prediction comparing the amount of time required for two blocks of unequal mass to fall a distance of 1 meter. Our hypothesized falling-objects schema for a typical uninstructed student includes the following features. Considering first the object category, the schema contains objects together with their observable physical properties, such as size, shape, and weight. Among the physics concepts in the schema are the object's properties including volume, mass, and weight, though these concepts are not precisely defined and are poorly differentiated; the objects' average speed in falling and the instantaneous speed at any point (two poorly differentiated concepts); the time elapsed during the fall; and a downward pull on the objects due to the pull, or, force of gravity. Here also is the concept, heavier than, in the sense of greater weight, and the specific application of this concept to the equal-sized objects of different

materials with the result that the metal block is conceived to be heavier than the plastic block. Relevant to this conception is the general rule, stored among the schema's experience-derived propositions, that "Heavier objects fall faster than lighter objects." In keeping with the uninstructed student's problem solving strategy (see the upper portion of Table 1), the relevant general rule is applied to the specific physical situation to deduce an answer for the problem. For the situation of the two blocks, the reasoning is: (1) The metal block is heavier than the plastic block. (2) Heavier objects fall faster than lighter objects. (3) Hence, the metal block falls faster than the plastic block. (4) The metal block takes less time to reach point O than the plastic block. The form of reasoning leading to the problem's solution is the same, of course, if the relevant general rule selected from the schema's stored propositions is: "According to Galileo, all objects fall at the same speed regardless of their weight." However, the answer to the problem now is that the metal and plastic blocks reach point O at the same time.

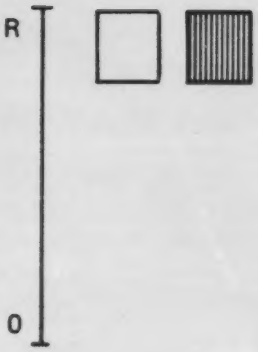
To transform the hypothesized problem-solving schema of the uninstructed student into a schema approximating an expert's schema requires changes such as the following. With regard to concepts in the schema, in place of concepts which are vaguely defined and poorly differentiated, the transformed schema's concepts have precise qualitative definitions which distinguish them one from the other. For instance, the concepts of <u>volume</u>, <u>mass</u>, and <u>weight</u> are differentiated from one another, and the definitions of <u>mass</u> and <u>weight</u> incorporate the relationships of these concepts to each other

and to major physical principles. In a similar position in the transformed schema is the concept of force, a generalized concept central in several major physical principles that was formerly represented only as a push or pull concept. With regard to principles in the student's new schema, in place of imprecise, experience-derived rules of limited scope and applicability, the transformed schema is dominated by a major physical law which is abstract and broadly applicable, specifically, Newton's Second Law of Motion. Associated with this law are its conditions of applicability, including (1) that the idealization assumptions of Newtonian mechanics are realized, and (2) that a constant net unbalanced force is acting on the objects of interest, here the plastic and metal blocks. Recognition that Newton's second law is applicable to this situation requires that the student's new schema include appropriate links between the abstractions of Newton's Second Law (mass, force, and acceleration); the physical objects (plastic and metal blocks, identical in shape and volume but differing in mass) and states specified by the problem (initial and final position, initial velocity is zero); and physical constructs not specifically mentioned or observed (force of gravity, acceleration, air resistance). These abstractions or second-order features, have no parallel in the student's initial schema and must be abstracted from the physical situation and the real objects therein in order for the student to link the physical situation with the Second Law. Examples of other second-order features are canonical objects, all of whose mass is concentrated at a single point, and vector representations of forces. Given that these second order features are

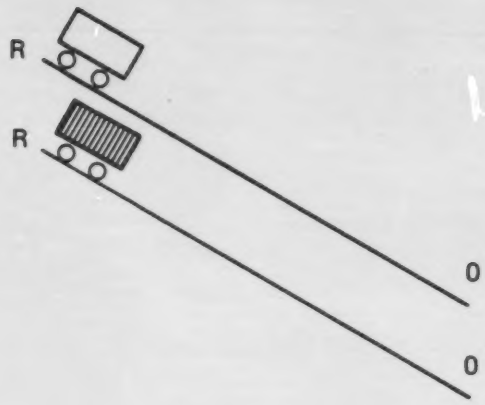
linked with physical objects, the three "real world" situations described in the problems in Figure 3 can all be represented abstractly as pairs of unequal masses (two blocks, two carts), each under the influence of a constant net force (gravity, extended rubber bands). Assuming the influence of friction is minimal, Newton's Second Law allows the student to predict constant acceleration for each of the objects and to compare the magnitude of the acceleration produced by unequal forces on unequal masses in the falling blocks and incline problems and on unequal masses under the influence of equal forces in the pulled carts problem.

Despite the numerous changes in the student's schema that we have surmised, some characteristics of the initial schema need not and should not change. In this category are the schema's representations of the physical objects themselves, their properties, and their described or suggested behavior. These are the representations that are utilized, we believe, to initiate the qualitative analysis of a mechanics problem.

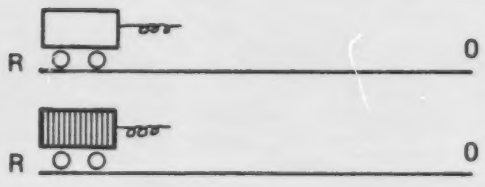
In order to explain and illustrate the instructional notion of the use of instructional dialogues to develop solution strategies for qualitative problems, we have analyzed a number of prototypical physics problems taken from introductory texts. One such analysis, which we will use now for the purposes of elaboration, is shown in Figure 4 while two others appear in Appendix A. The general structure of each analysis is simple. Initially the standard form of problem has been rewritten in qualitative form, with subsidiary questions asking about limitations of and physics principles used in the answer



Falling Blocks
The plastic block and the metal block are the same size and shape. Both blocks are held at point R. Then the two blocks are released at the same time and they fall the 1 meter distance to the floor. Compare the time for the plastic block to reach point 0 with the time for the metal block to reach point 0.



Carts on an Incline
The carts are the same size and shape and have the same wheels. One cart is loaded, the other is empty. They are on identical tracks. Starting from rest at R, both carts are released at the same time. Compare the time for the empty cart to reach point 0 with the time for the loaded cart to reach point 0.



Pulled Carts
The carts are the same size and shape and have the same wheels. One cart is loaded, the other is empty. They are on identical tracks. Starting from rest at R, both carts are pulled along the tracks so that the spring on each cart is always extended the same amount. Compare the time for the empty cart to reach point 0 with the time for the loaded cart to reach point 0.

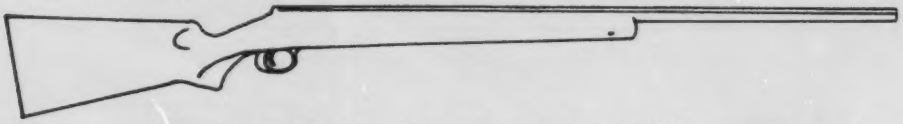
Figure 3. Three physics problems.

Original Problem

"1. A gun has a mass of 2.00 kg. It fires a bullet of mass 0.005 kg towards the right with a speed of 500 m/sec. How does the gun recoil? (Give its speed and direction of motion.)"

(Hulsizer & Lazarus, 1972, p. 187)

Problem Restated in Qualitative Form



When a gun is fired, the bullet leaves the gun with some speed. How does the bullet's speed at the muzzle of the gun compare with the gun's speed at that time? How does the direction of the bullet's motion compare with the direction of the gun's motion?

Subsidiary questions: (i) What assumptions did you make to arrive at your answers?
(ii) What principles of physics/laws of motion did you apply to the situation in coming to your answers?

Knowledge/skills assumed in following outlines of Instructional Dialogue strategies:

1. "Physics" knowledge: it is assumed that students have completed a study of kinematics.
2. General (or "world") knowledge: Awareness of medieval cannons, rifles, handguns (see step A1 below).

Strategy A Outline of strategy to be used for responses to the qualitative problem of the form "don't know" or "gun doesn't move."

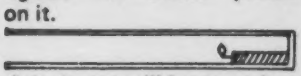
Steps in the Strategy	Purpose of Steps	Commentary on Steps
A1(a). Given *scale* drawings of a small pistol, rifle, small mortar, medieval cannon and shells/bullets fired by each, student is asked to match the guns and shells/bullets.	A1(a) and (b). To establish that, in the real world, mass/weight of gun ≥ mass/weight of bullet or shell.	Collins (1977) has proposed a series of production rules for this form of instructional dialogue. Strategy A1(a) is an example of Rule 1: Ask about a known case. In his subsequent reorganization of these rules (Collins & Stevens, in press), this is an example of Case Selection Strategy 1: Pick a positive exemplar for a set of factors.
A1(b). Ask student why matchings were made.		Collins (1977) Rule 2: Ask for any factors.[1]
A2. Ask the student why the bullet/shell comes out of the gun when the gun is fired.	To establish the role of explosion in this phenomenon. If this notion is present, go to A4; if not, go to A3.	Collins (1977) Rule 2 (see above).
A3. Show the student a drawing of a metal tube, closed at one end and with a lighted fire cracker placed on it.  Asked what will happen when the fire cracker goes off.	To establish the effect of explosion on the mass in the tube, i.e., the cracker. If this exercise does not establish the notion, move further to considering a medieval cannon where the explosive and propelled object are separate.	Collins (1977) Rule 3: Ask for intermediate factors. For some students this will also be a prompt to recall a relevant previous experience, relevant existing world knowledge.

Figure 4. Example of proposed instructional dialogue – The Gun and Bullet Problem.

Steps in the Strategy	Purpose of Steps	Commentary on Steps
A4. Using two laboratory trolleys, one containing a spring plunger (PSSC), and a number of bricks,[2]		
(a) have students experiment qualitatively with the effect of placing two carts with loaded spring between and releasing the spring, with varying masses on the carts,	To establish the separation of all masses involved in an explosion; to establish that smaller mass pieces move more quickly than larger mass pieces.[3]	Direct observation
(b) have students experiment with one cart carrying various masses placed with loaded spring against their hand and then released.	To establish that a mass exploded away from a "rigid" body results in a force on that rigid body.	Direct observation
A5. By drawing on A1-A4, assist the student to establish (and, if appropriate, to link to relevant existing knowledge/experience): (i) that in the case of the exploding carts, the expanding spring exerts forces on the carts placed at either end of the spring, and that these two forces are equal in magnitude. (ii) that, in the case of the exploding carts, equal forces from the spring acting on carts of different mass result in different cart velocities after explosion. (iii) that, in the case of exploding carts, when one cart has a mass considerably larger than the other this situation is in some ways analogous to a gun firing a bullet. (Of the limitations to the analogy, the most important to be drawn out here is that the relative mass differences for gun and bullet are much greater than for the carts.)	To establish the generalizations needed in order to be able to analyze and solve the original qualitative problem.	This step is similar to Step A1 (b) (see Footnote 1) in that the production rules to be applied will vary from subject to subject, depending both on each individual's existing knowledge and beliefs, and on each individual's interpretations of steps A1 to A4.
A6. Return to qualitative problem. After successful solution of the problem as asked, use strategy B below if appropriate.		

Figure 4. (continued)

Strategy B Outline of strategy to be used for responses to the qualitative problem of the form "speed of bullet very much greater than speed of gun and in opposite direction" (i.e., correct answer to questions asked).

	Steps in the Strategy	Purpose of Steps	Commentary on Steps
B1	Ask student if they can be more precise about the relative values of the bullet and gun speeds.	To establish that the ratio of speeds is the inverse ratio of the weights/masses involved. If this is not forthcoming, go to strategy A, beginning at A4. If some such statement is produced, go to B2.	Collins (1977) Rule 4: Ask for prior factors.
B2	Repeat subsidiary questions (i) and (ii) from the qualitative problem.	To elicit a statement of Newton's Third Law and to have the student authoritatively link this law to the gun/bullet phenomenon.	See commentary on Step A5.

1. Numbers of other rules (e.g., Rules 3-11) may be applied in the exploration of individual responses. For example, it may be necessary to ask "Could the cannon ball be fired from the pistol?" (Rule 6: Pick a counter example for an insufficient factor.)

2. Previous experience suggests that a physical mark (e.g., a chalk line) needs to be made to indicate the position of carts before the explosion so that a reference is available for considering post-explosion effects.

3. If friction effects provide an interfering concept, move further by using an air track for explosions and then returning to trolleys.

Figure 4. (continued)

given by the student. Then a realistic minimum state in terms of relevant prior knowledge and experience has been selected, and a strategy for working from that state to a successful solution has been proposed. At this stage, when we do not have the insights to be derived from data, it is assumed that other, more developed responses can be accomodated by beginning at a later point in this sample strategy. The strategy has been outlined only. It indicates a series of logical steps. Within each step, the essential concept(s) to be developed and the purpose of the step in terms of the problem solution are indicated. In some cases a particular instructional methodology to be used for a step is shown, while in the remaining cases only instructional dialogue is anticipated. For each step the rationale for the procedure is described, referring to the techniques identified by Collins (1977) and Collins and Stevens (in press) when appropriate. For each of the three examples, a strategy for handling a correct answer to the questions asked so as to develop a solution strategy for the problem is also given.

Physics problems and numerical exercises

The development of our ideas concerning the qualitative analysis of physics problems has led us to a simple but, we believe, most important reconceptualization of the nature of physics problems vis-a-vis the structure of standard physics texts and curricula. In what seems an obvious extension of the form of solution strategy applied to standard physics problems by experts, we wish to describe qualitative problems of the form given here as "Physics Problems." The

solution strategy derived for such a problem can then be applied to a set of exercises of the form currently termed problems. These exercises we wish to describe as "Numerical Examples." The parallels with mathematics learning are striking. The normal mode of instruction in math involves the development (or, unfortunately, the provision) of a solution strategy for a particular type of problem, for example, factorization of quadratics. Then students are asked to apply this solution strategy to numerical examples. These numerical examples are labelled by most texts and teachers with a description such as "Examples," "Exercises," etc., but are rarely termed "Problems."

This reconceptualization has, we believe, considerable instructional significance. Current practices seem to be based on the assumption that, by doing "Numerical Examples," students will themselves extrapolate solution strategies to "Problems." Texts commonly approach the task of elucidating methods for solving standard physics questions by giving "Numerical Examples" and, starting immediately with a formula, describing the appropriate approach. It is apparently assumed that this approach will be transferred by students to other appropriate "Numerical Examples," but instructional assistance for this transfer is rarely given. Indeed, as any practitioner of physics teaching can testify, assisting students to make such transfer is extraordinarily difficult. As a consequence, we argue that the methods outlined here are designed to foster the development of Problem solutions. We believe that solution of Numerical Examples is a subsequent and more simple step.

Instructional issues

Two issues which merit some consideration here arise from the instructional strategies we are advocating. First, our proposed strategies for the development of skills in qualitative analysis as a problem solution strategy make use of laboratory equipment in some cases (e.g., Step A5, Strategy A, in Figure 4). This use of laboratory-type experiences may be questioned since laboratory work has not been shown to produce significant cognitive gains for science students. Hence, it is necessary to discuss the specific conceptual basis for our use of laboratory-type experiences in the instruction. The second instructional issue to be discussed is the proper role of analogies in science instruction.

Role of laboratory experiences. Studies of instruction with laboratory work versus instruction without laboratory work have consistently suggested no cognitive advantage for the lab work group (see, for example, Bates, 1978, for a review). However, much laboratory work in the sciences in general and physics in particular can be characterized as follows: students follow some procedure for the collection of data, which is the prime focus of their activity whilst involved with the apparatus; results are then analyzed and, in many cases, subsidiary questions answered; the end result is the verification (or "discovery") of some law, relationship, effect of one variable on another, etc. This mode of laboratory work has most frequently resulted in students concentrating on the procedures for data collection and, overwhelmingly, on obtaining the correct answer. In such circumstances the apparent failure of laboratory activity to

markedly foster conceptual development does not seem surprising.

Gagne and White (1978, p. 214) have argued that laboratory work which is performed with the intent of facilitating understanding and conceptual development will better achieve such purposes if it seeks to generate links between episodes and images (derived from the laboratory work) and propositions and intellectual skills. This is an appealing argument, especially given the extent to which introspection reveals images and episodes in one's own memory which relate to specific facts and principles. However, Atkinson (1980), in comparing chemistry instruction with laboratory work and chemistry instruction with only demonstrations, found that the laboratory work did not appear to assist that group in recalling related subject matter even though this group was somewhat more likely to recall relevant images and episodes. Gunstone (1980), in an investigation of physics learning, found virtually no propositional connections between physics concepts which were derived from laboratory work. It is important to note that both of these two studies utilized laboratory work of the traditional format described above. It is, at the very least, plausible to suggest that laboratory work of this verification mode is unlikely, because of the focus it gives to student activity, to generate the image and episodic connections between propositions, concepts, etc. argued by Gagne and White.

Indirect support for the preceding argument is found in the work of Mackenzie (1979; White & Mackenzie, 1981). In an investigation of the impact of geographical fieldwork on memory structures and performance, three groups of high school students received class

instruction on coastal geography. One group received no field work, one undertook a field trip of similar focus to the characterization of laboratory work given above, and the third undertook a field trip specifically designed to generate episodes involving concepts which the field trip was intended to develop (e.g., rather than measuring increase in salinity in plants as distance from sea decreased, students chewed leaves from these plants). Although both fieldwork groups performed significantly better than the remaining group on tests of immediate learning, the episode-generating fieldwork group had substantially better three-month retention scores and substantially greater linkage between episodes and knowledge/concepts (as tested) on both testing occasions.

In considering the lack of cognitive gain from traditional laboratory work, White (1979) has argued for the inclusion of three types of practical activities not usually found in science courses. One of these types is used in the strategies for developing problem solutions which are outlined in Figure 4 and Appendix A. This type

> is intended to establish generalized episodes involving materials and events of common experience, with the purposes of linking school subject matter and daily life and of providing experiences which will be called into play in making subsequent information comprehensible. (White, 1979, p. 387)

Directed hands-on experience with physical objects is included in our strategies because of the extent to which such experience can relate aspects of the problem to relevant prior experience in the world at large, can provide sensory inputs about situations, and can provide episodes or images as memory structures for later recall. It

is of interest to note that this overt attempt to bring to the problem solution relevant real world knowledge is in line with arguments for the importance of such knowledge to the individual's problem solution (see, for example, Duran, 1980; Neisser, 1976). Others (e.g., West, 1980) have probed students' links between "curriculum knowledge" and general knowledge as an important dimension of students' cognitive structures.

This rationale for a particular form of laboratory work will be briefly illustrated by reference to the proposed strategy for the gun and bullet problem in Figure 4. The use of spring-loaded, exploding carts illustrates the basic principles underlying the gun and bullet problem. By manipulating masses, students will derive qualitative relationships between the relevant variables, be assisted to relate these relationships to the underlying physics principles and, perhaps most importantly, be given a memorial referent to which to relate this information. In addition, some students will relate this experimental manipulation to previous relevant experience, for example, pushing peers while skating. Before the event it is clearly not possible to determine which students have relevant prior experience. Hence, the drawing out and relating of any such experience will be achieved by the instructional approach to be used.

Seen in this light, the use of the exploding carts can be clearly characterized as an attempt to provide a physical analogy to the gun and bullet. This use of analogy leads to the second issue to arise from the analysis of solution strategies for qualitative problems. That issue concerns the instructional dangers of the use of analogies.

Analogies in instruction. The role of analogies, and models as formalized or even institutionalized analogies in the development of science, has been widely discussed by philosophers of science. Further, much has been written about the manner in which analogies can inhibit or distort the development of science when inappropriate deductions are made on the basis of existing analogies. (See, for example, Harre, 1965; Nagel, 1961; Scheffler, 1969.) There is an analogous situation in science instruction. As Gee (1978) and Weller (1970) have indicated, the use of analogies in instruction can result in students extending the analogy in inappropriate ways to generate false information. White and Gunstone (1980), in an investigation of cognitive structures associated with electricity, found a clear and extreme example of such a phenomenon. A college science graduate who had been given the water flow analogy during his early instructional experience with electric current had extended the analogy on his own initiative so as to equate the functions of a pipe in the water analogy and the insulation surrounding a conducting wire. As a consequence, he believed resistance to electric current arose from the friction between electricity and the surrounding insulation, he believed that electrical leakage was akin to a hole in a water pipe and that it could result from a bare electrical conductor, and he had deduced that much of the research effort in electrical engineering was devoted to the production of more efficient (i.e. less friction-generating) insulating covers for wires.

In short, we believe that an important and neglected aspect of the instructional use of analogies is an understanding of the

limitations of the analogy. We believe that developing such understanding also adds to the understanding of the science concept which the analogy is used to illustrate. Consequently, we are explicit about significant limitations to be developed with students when using hands-on experience to provide analogies to the qualitative problem situations.

Some Aspects of Proposed Research

We have already indicated that we intend to investigate some of the issues which have been argued above. The major hypothesis to be tested in our proposed research is that engaging beginning physics students in instructional dialogues within a context of the qualitative analysis of mechanics problems will produce changes in the students' motion-of-objects schemata. Our further hypothesis is that, after completion of the specified instruction, the students' schemata will have several significant features which are characteristic of the mechanics schema of a physics expert.

Our first task in this research is to specify the scope and sequence of questions and manipulative experiences which will serve as the stimuli for the instructional dialogue. An example of the stimulus materials and the rationale for their construction is exhibited in Figure 4. Two further examples appear in Appendix A. From analyses similar to these for every problem we select for the instruction we can derive specifications for the issues which need to be raised, the topics which will be discussed in the instructional

dialogues, and the laboratory-type experiences which are required to provide essential observations or episodes. With the general strategies and the content of the instruction specified, the final design task is to incorporate these into instructional materials.

As exemplified by the three physics problems shown in Figure 3, we plan to select problems to form a sequence in which the problems, though differing in surface features, can all be solved by making essentially the same qualitative analysis and by utilizing the same physical principle. There will be several such sequences in the instruction, whose scope is an introduction to dynamics under the purview of Newton's Laws of Motion. The specific problem sequences to be included in the instruction will be determined by our analyses of which topics are necessary to induce changes in students' schemata and by determining how far along the continuum of approximating the physics expert's schema we wish the students to proceed.

For assessing the students' motion-of-objects schemata before and after instruction, we shall use several different techniques drawn from our own and other researchers' studies. Each technique probes cognitive structure in a somewhat different fashion, yielding its unique shards of data for analysis. By combining the results of the analyses of the data from several sources, we can infer a fairly extensive portion of the content of students' schemata. The assessment techniques we plan to use and the kinds of information obtained from analyses of data from them include the following.

DOE (Demonstrate, Observe, Explain) Tasks are one kind of probe of cognitive structure we have used in previous studies (e.g.,

Champagne et al., 1980a, 1980b). In a DOE Task, students predict the outcome of a demonstration and give reasons for their predictions. After seeing the demonstration, they report what they observed and note whether or not it accords with their prediction. If the observation and prediction are discrepant in any way, they explain the discrepancy. We shall use several different DOE Tasks, each demonstrating some instance of objects in motion, in the student assessments. From the analyses of the students' responses, we shall identify the specific conceptions and misconceptions about motion, both its kinematic and dynamic aspects, that the students hold. We shall also learn how well they differentiate various mechanics concepts and see the nature of the propositions they employ to reason about physical events.

The interview-about-instances technique (Osborne and Gilbert, 1980) makes it possible to gain insight into students' views about selected concepts, say the concept of force, and the meanings they have for the words they use in discussing the concepts. For each targeted concept, the student works with a set of picture cards, each depicting an instance of the concept in real-world context. Two kinds of data are collected, the first being the results of the student's sorting of the cards into groups and his or her explanation of the self-selected criteria for grouping. Second, interview protocol data are obtained as the student explains why he or she believes that the picture on each card either is or is not an instance of the targeted concept (e.g., Is there a force on the golf ball?). We shall use the interview-about-instances technique for several key mechanics

concepts, including force, acceleration, and mass, to identify what each student's meaning for the concept is and how the student relates it to other concepts.

Asking subjects to sort physics problems into types according to their own criteria and obtaining think-aloud protocols as subjects solve problems are two techniques used to study the representation of physics problems by experts and novices (Chi et al., in press). We shall apply these techniques in our student assessments, except we shall restrict the domain to the qualitative mechanics problems in which we are interested. From analyses of the students' performances and explanations, we shall learn whether the student attends to surface features or to second-order features in analyzing problems, and we shall be able to infer whether the student's schema is oriented by the objects of the problem of by a physical principle.

For monitoring of the students' schema changes as they engage in instructional dialogues, techniques of protocol analysis will be applied. Issues around the analysis procedures and the validity of protocol data are discussed in Erickson & Simon (1980). In each of the instructional steps, features of hypothesized schema changes will be described.

Concluding Remarks

We can admire the great psychologists of earlier days, such as Charles H. Judd, whom we quoted at the start of the paper, for their keen perspective on students' learning of obtruse school subjects like physics. Judd's insight (or perhaps, intuition) seems so right and true that we cannot help being amazed. Also amazing is the realization that the situation which Judd described seven decades ago still rings true for physics textbooks and physics learning today. Hardly anything seems to have changed in the interim. Why is this so?

The main reason, we believe, is that, although Judd recognized the problem, he could not prescribe an effective solution. Because he was unable to describe the problem precisely, Judd had no basis on which to evaluate the probability of the effectiveness of possible instructional strategies. Today the status is different. Empirical and theoretical research in cognitive psychology make possible the construction of theoretical models, on which predictions can be based. The application of a model of understanding of physical phenomena leads to detailed specification of a strategy for beginning physics instruction which can be expected to produce desired changes in students. The difference between our present possibilities and those of Judd's day is demonstrated in this paper.

Appendix A

Two Further Analyses of Qualitative Mechanics Problems

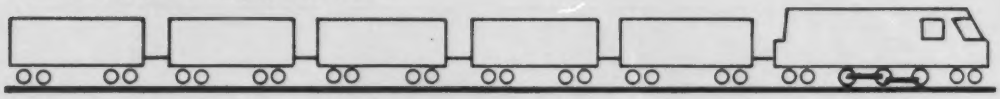
Problem 1: The Train Problem

Original Problem

"9. A freight engine of mass 20,000 kg accelerates from rest up to a velocity of 2.0 m/sec. in 5.0 sec. If it is pulling a train of 20 cars, each with a mass of 10,000 kg, what is the force in the coupling between the engine and the first car?"

(Stollberg & Hill, 1964, p. 49)

Problem Restated in Qualitative Form



A freight train is stationary. It then accelerates away from rest. Whilst the train is accelerating, how does the force exerted by the engine to accelerate the train compare with the force in the coupling between the engine and the first car?

Subsidiary questions: **(i) What assumptions did you make to arrive at your answer?**
(ii) What principles of physics/laws of motion did you apply to the situation in coming to your answer?

Knowledge/skills assumed in following outline of Instructional Dialogue strategies:

1. It is assumed that students
   (a) have completed a study of kinematics and Newton's Laws
   (b) are aware that the extension of a rubber band or spring is a reasonable indicator of the magnitude of the extending forces acting on the rubber band or spring.
2. It is also assumed that there is instructional value in students having both visual and touch inputs of estimations of the magnitude of forces.

Strategy A Outline of strategy to be used for responses to the qualitative problem of the form "don't know" or "the same."

Steps in the Strategy	Purpose of Steps	Commentary on Steps
A1. Have the student pull, using a rubber band, laboratory trolleys (PSSC) carrying various numbers of bricks.	To draw attention to, or re-establish, the qualitative relationship between mass, motion of the mass, and applied force.	Direct observation. Questions to assist processing of the observations would follow, for example, Collins (1977) Rule 1: Ask about a known case, and Rule 11: Specify how the variable depends on a given factor. Specific procedural rules will vary between individuals.
A2. Use two trolleys connected by a rubber band arranged so that the trolleys are almost touching when stationary – hence separation of trolleys is an indicator of extension of that rubber band.	(a) To establish what specific objects each of the two rubberbands is pulling. (b) To direct attention to the qualitative relationship between mass and force required to accelerate that mass.	As for A1 above. Possible procedural rules include 13: Probe for differences between two cases; and 11 (see above).

Steps in the Strategy	Purpose of Steps	Commentary on Steps
Have the student pull the trolleys by a rubber band attached to cart 1.		
A3. Repeat A2 with various masses added to cart 1 and/or cart 2.	See purpose (b) in A2.	See A2 above.
A4. Repeat A2 and A3 using a number of carts.	See purpose (a) & (b) in A2.	See A2 above.
A5. Return to qualitative problem. After successful solution of the problem as asked, use strategy B below, if appropriate.		

Strategy B Outline of strategy to be used for responses to the qualative problem of the form "force exerted by the engine is greater than the force in the coupling" (i.e., correct response to question asked).

Steps in Strategy	Purpose of Steps	Commentary on Steps
B1. Ask student if they can be more precise about the relative magnitudes of the two forces.	To establish that ratio of forces is inverse of ratio of total mass/weight of train to mass/weight of cars pulled by the engine. If this is not forthcoming, go to strategy A, beginning at A2. If some such statement is produced, go to B2.	Collins (1977) Rule 4: Ask for prior factors.
B2. Repeat subsidiary questions (i) and (ii) from the qualititive problem.	To link answers to the subsidiary questions to the specific stiuations presented – both the experiences with carts and the qualitative problem.	See Commentary on Step A5 in Figure 1.

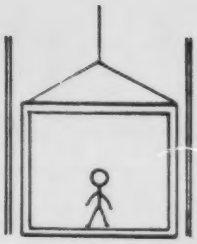
Problem 2: The Man in Elevator Problem

Original Problem

"6.23 A 75-kg man carrying a 12-kg suitcase rides in an elevator that has an upward acceleration of 0.50 m/sec. Find (a) the pull on his arm and (b) the force with which his feet press on the floor of the car, each expressed as a multiple of the weight of the supported object or system."

(Freeman, 1973, p. 141)

Problem Restated in Qualitative Form (and also simplified by removing one of the two problems in the original so that the development of a solution logic for one situation can be the focus of the theaching strategy).



A person stands in an elevator which is not moving. The elevator accelerates upwards to take the person to higher floors in the building. How does the force with which the person's feet push on the elevator floor compare with the person's weight whilst the elevator is accelerating upwards?

Subsidiary questions: (i) **What assumptions did you make to arrive at your answer?**
(ii) **What principles of physics/laws of motion did you apply to the situation in coming to your answer?**

Knowledge/skills assumed in following outlines of Instructional Dialogue strategies: as for Problem 1 above.

Strategy A Outline of strategy to be used for responses to the qualitative problem of the form "don't know" or "the same" or "there is no connection between the sizes of those forces."

Steps in the Strategy	Purpose of Steps	Commentary on Steps
A1(a). Consider (any object) placed on a table in front of the student. ask what forces are acting on the object.	To probe the student's notion of normal reaction and force exerted by object on table. If these are not understood, go to A2; if they are, go to A1(b).	Collins (1977) Rule 1: Ask about a known case, for students who understand. For students who do not, see A2.
A1(b). Ask student why the normal reaction force is present.	To establish whether student understands the origins of the reaction force, If yes, go to A3; if not, go to the appropriate section of A2.	Collins (1977) Rule 2: Ask for any factors.
A2. A comprehensive teaching strategy, consistent with the philosophy underlying the present approach, for assisting the development of the concept normal reaction has previously been described (Minstrell, n.d.). This would be used here.		
A3. Have student suspend an object from a rubber band. Ask student about forces acting on the object.	(a) To establish that, in this condition, weight force = force exerted by rubber band on object. (b) To establish the analogy, with respect to forces acting, of this situation to that used in A1.	Direct observation. Collins (1977) Rule 2: Ask for any factors.
A4. Have student accelerate their hand upwards whilst holding the rubber band and suspended object. Ask about forces on the object during this motion.	(a) To establish that force exerted by rubber band on object is greater than in A3. (b) To establish that a net force upwards exists when the object is accelerated up-	Direct observation. Collins (1977) Rule 2: Ask for any factors.

Steps in Strategy	Purpose of Steps	Commentary on Steps
	wards, and that magnitude of this net force is related to the additional extension of the rubber band. (c) To relate these observations and deductions to F = ma.	
A5. Use the analogy developed in A3 to relate the observations and deductions from A4 to the situations given in the initial problem.	As stated in Step A5.	See commentary on step A1, problem 1 above.
A6. Return to qualitative problem. After successful solution of the problem as asked, use strategy B below if appropriate.		

Strategy B Outline of strategy to be used for responses to the qualitative problem of the form "feet push on floor with a force greater than the person's weight" (i.e., correct answer to the question asked).

Steps in Strategy	Purpose of Steps	Commentary on Steps
B1. Ask student if they can be more precise about the relative magnitudes of the two forces.	To establish that magnitude of acceleration is related to magnitude of the difference between the two forces. If this is not forthcoming go to strategy A, probably step A3, although the concept of normal reaction should be probed. If some such statement is produced. go to B2.	Collins (1977) Rule 4: Ask for prior factors.
B2. Repeat subsidiary questions (i) and (ii) from the qualitative problem.	To link answers to the subsidiary questions to both the situations with the rubber band and the qualitiative problem.	See commentary on Step A5 in Figure 1.

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